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ACCELERATION OF CHARGED PARTICLES IN THE INTERPLANETARY PLASMA

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ABSTRACT. This discussion concerns the nature of the second peak of fast protons which appears after the coming of a diffusive wave from a solar flare. The presence of the fast proton peak is connected with acceleration of particles by fluctuation fields in the interplanetary plasma.

1. The flights of the Zond-3, Venera-2, Mariner-4, and Pioneer-6 interplanetary stations have made possible an important series of studies of the solar cosmic rays [1]. An increase of the proton intensity accompanying solar flares was recorded during these flights. Of particular interest are the solar cosmic ray flares which occur with a considerable delay (1-3 days) with respect to the flare on the sun. Flares of this type are accompanied by a magnetic storm with a sudden beginning, and also by a Forbush effect with a steep phase falloff and a deep minimum. Such flares were recorded on 20 January 1966 and 25 June 1967. Two possible versions of the explanation for flares of this type are known. The first is that the acceleration of the particles takes place at the sun and the major portion of the accelerated particles moves together with the ejected plasma and reaches the observation points after the shock wave front has passed [2]. We shall examine the second version, in which the acceleration of the particles does not take place at the sun but in the interplanetary plasma [3] in which, as will be shown later, large fluctuations of the electromagnetic fields are possible. /1019*

2. It is known that during injection of corpuscular fluxes into the plasma in the near-Earth space there may be created a sharp transitional layer [4], in which intense agitation of the plasma may occur. As a result of the accumulation

* Numbers in the margins indicate pagination in the original foreign text.

effect the energy of the turbulent pulsations increases rapidly, reaching a limiting value. After this a stationary distribution of the turbulent pulsations is established [3, 4]. We can suppose that the occurrence of such a plasma explains certain of the experimental data indicating the presence of accelerated particles in the interplanetary medium.

We shall start from the Fokker-Planck equation

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial p_i} D_{il} \frac{\partial f}{\partial p_j}, \tag{1}$$

where D_{ij} is the diffusion coefficient tensor, which in an isotropic plasma may be written in the form

$$D_{il} = \frac{p_i p_j}{p^2} D_{\parallel} + \left(\delta_{ij} - \frac{p_i p_j}{p^2}\right) D_{\perp}. \tag{2}$$

If the particle energy depends only on the absolute value of the momentum, the equation for the particle energy change may be written in the form [4]

$$\frac{\partial \langle \varepsilon \rangle}{\partial t} = \langle \frac{1}{p^2} \frac{\partial}{\partial p} D_{\parallel} p^2 \frac{\partial \varepsilon}{\partial p} \rangle, \tag{3}$$

where

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$$\langle \varepsilon \rangle = \int \varepsilon f d\mathbf{p}.$$

In the nonrelativistic case the diffusion coefficient $D_{\parallel}$ is completely defined by the spectral distribution of the fluctuations of the longitudinal electric field in the plasma

$$D_{\parallel} = \frac{q^2}{8\pi^3 \mu^2 v^2} \int d\mathbf{k} \frac{\omega^2}{k^2} \langle E_{\parallel}^2 \rangle_{k\omega}, \quad \omega = \mathbf{kv}, \tag{4}$$

where q, μ, $\mathbf{v}$ are the charge, mass, and velocity of the accelerated particle; $\langle E_{\parallel}^2 \rangle_{k\omega}$ is the longitudinal electric field correlator. If we know the spectral distribution of the field fluctuations in the nonequilibrium plasma, (3) and (4) make it possible to study the charged particle acceleration process.

Consider fluctuations in a plasma consisting of cold ions and hot electrons, moving relative to the ions with the velocity **u**. The electric field fluctuation correlator in such a plasma has the form [5]

$$\langle E_{\parallel}^2 \rangle_{k\omega} = 8\pi^2 T_e a_e^2 v_s^2 k^4 (1 + a_e^2 k^2)^{-2} |\omega - \mathbf{ku}|^{-1} \delta(\omega^2 - \omega_k^2), \tag{5}$$

where

$$a_e^2 = \frac{T_e}{4\pi e^2 n_0}, \quad v_s = \sqrt{\frac{T_e}{m_i}}, \quad \omega_k = \frac{k v_s}{(1 + a_e^2 k^2)^{1/2}}.$$

From (3) and (5), we find the effect of particle acceleration by ion sound waves

$$\frac{\partial}{\partial t}\langle \varepsilon \rangle = \left\langle \frac{\alpha}{\varepsilon (v\cos\vartheta - v_s)^2} \right\rangle, \tag{6}$$

where

$$\alpha = 2q^2 v_s^2 \Omega_e^2 \left(\frac{m_e}{\mu}\right)\left(\frac{T_e}{T_i}\right)^2$$

(θ is the angle between **u** and **v**).

If there is in the plasma a beam with velocity of the order of the critical velocity, above which instability of the Langmuir waves begins, the electric field fluctuation correlator has the form [5, 6]

$$\langle E_{\parallel}^2 \rangle_{k\omega} = 8\pi^2 T \Omega_e^2 |\omega - \mathbf{ku}|^{-1} \delta(\omega^2 - \Omega_e^2), \tag{7}$$

where $\Omega_e^2 = 4\pi e^2 n_0 / m_e$; **u**, T, n_0 are the average velocity, temperature, and density of the beam. From (3) and (7), we find the effect of particle acceleration by Langmuir waves

$$\frac{\partial}{\partial t}\langle \varepsilon \rangle = \left\langle \frac{\beta}{\varepsilon^{3/2}\left(1 - \frac{u}{v}\cos\vartheta\right)} \right\rangle, \tag{8}$$

where

$$\beta = \frac{2q^2\Omega_e^2 T}{(2\mu)^{3/2}}.$$

Langmuir waves can accelerate particles whose velocity $u \gtrsim v_{T_e} = \sqrt{\frac{T_e}{m_e}}$. Ion sound waves can accelerate particles with velocity of the order of $v_s \gtrsim v_{T_i} = \sqrt{\frac{T_i}{m_i}}$ and can inject them into the high-frequency wave acceleration regime.

In the limiting case of high velocities for the ion sound waves, we have from (6)

$$\frac{d}{dt}\langle \varepsilon \rangle = 2\mu\alpha \langle \varepsilon^{-2} \rangle \quad (v\cos\vartheta \gg v_s). \tag{9}$$

For the Langmuir waves in this case (8) takes the form

$$\frac{d}{dt}\langle \varepsilon \rangle = \beta \langle \varepsilon^{-3/2} \rangle \quad (v \gg u\cos\vartheta). \tag{10}$$

3. It is of interest to find the spectrum of the accelerated particles. The total number of particles in the acceleration region is determined from [8]

$$\frac{\partial}{\partial t} N(\varepsilon, t) = -\frac{\partial}{\partial \varepsilon}\left(N(\varepsilon, t)\frac{d\varepsilon}{dt}\right) - \frac{N(\varepsilon, t)}{\tau_c} + q_i(\varepsilon, t), \tag{11}$$

where τ_c is the average particle accumulation time in the accelerating volume. $q_i(\varepsilon,t)$ is the source function, defined by the injection velocity, $d\varepsilon/dt$ is the rate of increase of the particle energy during acceleration. The rate of acceleration by the ion sound waves is defined by (9), and that by the Langmuir waves is defined by (10). If the acceleration is terminated at the time t_0, where $\tau_c \ll t_0$, then the stationary state $dN/dt = 0$ will be reached shortly after initiation of the acceleration. Then (11) for ion sound waves may be written in the form

$$N = C_1\varepsilon^2 \exp\left(-\frac{\varepsilon^3}{6\mu\alpha\tau_c}\right),$$

where $C_1 = \frac{1}{2\mu\alpha}\int_0^{\varepsilon_i} q_i \exp(\varepsilon^3/6\mu\alpha\tau_c)\, d\varepsilon$, ε_i is the injection energy.

Similarly, for the Langmuir waves

$$N = C_2\varepsilon^{3/2}\exp(-2\varepsilon^{5/2}/5\beta\tau_c),$$

where

$$C_2 = \frac{1}{\beta}\int_0^{\varepsilon_i} q_i \exp(2\varepsilon^{5/2}/5\beta\tau_c)\, d\varepsilon.$$

4. From the known parameters of the interplanetary plasma [8] $n \approx 5$ см$^{-3}$, $\frac{T_e}{T_i} \approx 10$, from (10) we find $\varepsilon \sim 10^4$ t eV/sec. According to the data of [7], the acceleration time is of the order of 10^5 sec. Then $\varepsilon \sim 10^9$. Measurement results [8] show that the increase of the cosmic ray intensity is caused by particles with energies $\varepsilon \gtrsim 1{,}5\cdot 10^9$ eV. Thus, the presence of a second maximum of the fast proton intensity, occurring after a magnetic storm, may be associated with particle acceleration by the fluctuation fields in the interplanetary medium.

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